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Comparison of Cost Efficiency of Mechanized Fuel Wood Thinning Systems for Hardwood Plantations on Farmland

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Abstract

A harwarder is a machine used for both wood harvesting and extraction. A small and a large harwarder (SH and LH) were time studied whilst thinning hardwood plantations established on agricultural land in Italy. Two treatments were studied: whole tree sections (WT) or firewood logs integrated with tree tops (IH) were harvested and forwarded to the roadside. The selective thinning yielded 45 tonnes of fresh biomass (t) per hectare. The average productivity of the SH and LH with the WT harvesting treatment were 3.46 and 2.77 t per gross productive work hour, respectively. The SH was more efficient for felling and loading, while the LH was more efficient in the terrain transport work. The productivity of both machines was about 15% lower for IH treatment. The harwarder based thinning operation gave a harvesting cost between 18 and 34 €/t under the conditions studied. Thus, the operational cost per t of the SH was less than for the LH. The harvesting cost decreased with increasing size of harvested trees for both machines. The level of stand damage caused by both harwarders was almost as low as the levels recorded in the literature for motor-manual thinning. The LH was able to handle larger trees than the SH in the studied conditions. The LH gives higher flexibility, since it can be used more efficiently in thinning of larger trees and in larger plantations than in the present study.

Keywords: harvesting, harwarder, firewood, biomass, agricultural land

1. Introduction

In the early 1990s, the EU launched a new afforestation programme, with the intention of controlling agricultural production, reducing the shortage of wood products and achieving a number of social and environmental benefits (Tassone et al. 2004). This programme was bolstered by a number of ambitious funding schemes, offering specific grants for the afforestation of arable land (Kassioumis et al. 2004). By the end of the 1990s, approximately 900,000 ha of land across the EU had been afforested with both softwood and hardwood (Du Breil 2000, Cogliastro et al. 2007). More hectares were planted in the following years, causing a significant increase in the European forest area. 148,000 ha of new plantations had been established in Italy by the year 2000, of which ca. 60% were planted with hardwood species (Magnani et al. 2005). The most popular species were walnut (*Juglans regia* L.) and cherry (*Prunus avium* L.), which offered both fast growth and high-quality timber (Gold and Hanover 1987, Dupraz 1994).

In general, the plantations were established with two or more main crop species, often combined with nurse tree species, which provide side protection and improve bole quality (Bohanek and Groninger 2003, Cutter et al. 2004).

Currently, the success of these plantations depends on their capacity to produce good quality stem wood within a relatively short time, estimated to be between 30 and 40 years (Mary et al. 1999). Timely thinning has a crucial role to play in the selection of the best trees, maintaining the right density and preventing fast growing nurse trees from overtopping the main crop (Bohanek and Groninger 2005).

Usually, early thinnings generate poor financial returns due to the handling of small trees, which have relatively low financial value but have a relatively high operational cost per unit harvested (Kärhä et al. 2003, Spinelli and Magagnotti 2010). Traditionally, forest owners can balance the cost of thinning young forests with revenues drawn from harvest of older forests. That is not the case with the new plantations, which were all planted in the same period. Furthermore, tree plantations on farmland are often small and scattered, which makes machine relocations a critical cost issue (Spinelli et al. 2009).

Given the large area planted in the last two decades, Europe is facing a serious forest management problem and risk to miss an opportunity to obtain much needed biomass. In thinning stands, where a large share of the cut trees are undersized for e.g. pulp production, a fuel wood harvest, or a combined fuel wood and pulp wood harvest, may yield higher profits compared to a pure roundwood harvest (cf. Di Fulvio and Bergström 2013). Therefore, the key issue is to develop effective work systems that can make thinning of the new hardwood plantations established on ex-arable land financially viable. A possible solution can be the use of a single machine system that combines the harvester and forwarder work, a harwarder. The main advantages of this machine system are that:

⇒ an entrepreneur owns and relocates only one machine at a time (Asikainen 2004),

⇒ its productivity, compared to a dual machine system, can also achieve a similar level for short hauling distances.

For this reason, the harwarder may offer a lower harvesting cost compared to the standard harvester and forwarder system when the thinning intensity is below 55 m^3 ha^{-1} (Kärhä 2006) and/or stand size is below a biomass removal <250 m^3 (Väätäinen et al. 2006a). Furthermore, some harwarders can be driven on public roads and can therefore be independently relocated over short distances, without needing a truck and trailer unit.

The objective of this work was to study the productivity and cost efficiency of harwarder systems used for fuel wood thinning of hardwood plantations. The following factors were considered: two machine sizes (small or large) and two products harvested (parts of whole trees or firewood logs and tree tops). The impact of the machines on the ground and remaining trees was also measured and compared.

2. Materials and methods

Two different thinning systems were considered: Whole Tree (WT); harvesting and forwarding of undelimbed whole-tree sections to the roadside and Integrated Harvesting (IH); integrated harvesting of firewood logs and tree tops, with the two assortments separately forwarded to the roadside. Each thinning system was combined with two sizes of harwarder, »small« (SH) and »large« (LH), giving four unique treatments studied in the field.

2.1 Study sites

Two sites in Italy were used for the trials, one located in San Daniele (46°08'N, 13°00'E) and one in Persereano (45°57'N, 13°17'E) (Table 1). The stand in San Daniele was 15 years old and was planted in rows spaced 4x2 m, with cherry (*Prunus avium* L.), European walnut (*Juglans regia* L.) and common ash (*Fraxinus excelsior* L.), the latter acting as a nurse tree. The stand in Persereano was 17 years old and was planted in rows spaced 4x3 m, with sessile oak (*Quercus robur* L.), cherry, sycamore maple (*Acer pseudoplatanus* L.) and common ash, the latter two species acting as nurse trees. 12 plots were located in San Daniele and 4 in Persereano. Each plot measured 50x40 m and was randomly assigned to each treatment, in order to allow evenly spread conditions for comparison. Each treatment was repeated four times, giving a total of 16 repetitions.

Table 1 Stand characteristics of study sites: average values (standard deviation in parentheses)

Stand	San Daniele	Persereano
Plots, n	12	4
DBH, cm[a]	12.5 (1.2)	13.8 (1.0)
Density, trees/ha	1,187 (23)	853 (16)
Basal area, m^2/ha	14.8 (2.2)	12.8 (1.0)
Dry mass, odt/ha[b]	58.4 (11.2)	52.5 (4.1)
Dry mass per tree, odkg[b]	49.3 (10.2)	61.6 (4.6)
Fresh mass, t/ha[bc]	94.2 (18.1)	84.7 (6.6)
Fresh mass per tree, kg[bc]	79.5 (16.5)	99.4 (7.4)

[a] Mean diameter weighted by basal area
[b] Estimated by means of dendrometric parameters
[c] Estimated fresh mass, for wood with a moisture content of 38%

2.2 Harvesting and chipping systems

The SH was a Vimek Biocombi 610 (Vimek AB, Sweden, www.vimek.se), with 6 wheels, a 44 kW engine and a weight of 4.9 t. It was equipped with a crane with a reach of 5.2 m which, in turn, was equipped with a Hypro grapple-saw fitted with accumulating arms. The machine had a loading bunk with compacting stakes for load-compression. The LH was a Pfanzelt Felix 206 (Pfanzelt Maschinenbau GmbH, www.pfanzelt-maschinenbau.de), with 4 wheels and a 130 kW engine. It was equipped with a crane with a reach of 8.5 m. The boom tip was equipped with a quick connection device for time-efficient changing of heads. The heads used on the machine were a Logmax 5000 harvester head and a timber grapple for roundwood. The machine had an extendable load bunk and the complete unit weighed 14 t.

All machines were operated by experienced operators, who had run their machines for several years but had no experience of these types of plantations.

2.3 Work methods

Both sites were thinned selectively, in order to create enough space around good quality crop trees, while removing the trees that were defective in some way, or direct competitors. The thinning intensity ranged between 40% and 55% of the initial tree density per ha. At the time of harvest, the trees to be cut had already been selected and marked.

The SH thinned 2 rows of plantation per swath. In the WT treatment, the trees were cut and directly loaded onto the load bunk; the tree tops were first cut on the standing trees, then the butt log was felled and loaded. In the IH treatment, ca. 3–4 m long tree tops were cut off from the standing tree and directly loaded onto the bunk. Subsequently, in a separate load, the firewood butt logs were cut and directly loaded.

The LH carried out cutting and forwarding as separate operations. It cut 2–4 rows per swath. In the WT treatment, trees were cut and bucked in ca. 5 m lengths. Tree branches were compressed with the harvester head while feeding the material through the head. Bunched tree sections were piled along strip-roads. In the IH treatment, separate piles were produced for firewood logs and treetops. Subsequently, the harvesting head was switched for the timber grapple and the load space was extended for forwarding work.

2.4 Time study

The time study was carried out between the 21st and 25th of October 2013. It was carried out during daylight; there was some rainfall during the study. The time consumption per plot and machine configuration was measured using a Husky Hunter™ field computer running Siwork 3 software. Recording was carried out at 0.6 s intervals (100 per minute).

The net work-time elements cutting and loading (i.e. including crane movement time from first to last tree cuts per crane cycle and loading while moving), driving loaded/unloaded, unloading work time and the delay times were all separately measured (cf. Magagnotti and Spinelli 2012). The sum of the net work-time elements was used as the Productive Machine work time (PM_0).

PM_0 was converted to gross productive work time (PMH_{15}), which includes delays shorter than 15 minutes. Delay time is, however, typically erratic and its magnitude may vary greatly over time. Thus, it is most probably incorrectly measured when measured over short periods, as in this study (c.f. Spinelli and Visser 2008). For this reason a delay factor of 0.835 was used to convert PMH_0 to PMH_{15} for the two harwarders according to Kuitto et al. (1994).

2.5 Field measurements

The harvested mass per plot and load were weighed using a portable plate scale. Different products were weighed separately. At the end of the trial,

Table 2 Cost assumptions and machine hourly rates

Machine	Small harwarder SH	Large harwarder LH
Investment , €*	145,000	350,000
Resale (20%), €	29,000	70,000
Service life, years	6	8
Utilization, PMH_{15} year^{-1}	1,400	1,400
Interest rate, %	4%	4%
Depreciation, € year^{-1}	19,333	35,000
Interests, € year^{-1}	3,867	9,100
Insurance, € year^{-1}	2,500	2,500
Diesel, € year^{-1}	9,450	16,800
Lubricant, € year^{-1}	945	1,680
Maintenance, € year^{-1}	9,667	17,500
Total, € year^{-1}	45,762	82,580
Total, € PMH_{15}^{-1}	32.7	59.0
Crew, n.	1	1
Labour, € PMH_{15}^{-1}	20	20
Overheads (20%), € PMH_{15}^{-1}	10.5	15.8
Machine rate, € PMH_{15}^{-1}	63.2	94.8

* The investment cost was obtained from the manufacturers and was based on 2013 price lists

all the biomass was chipped and transported for weighing at a certified weighbridge. Weighbridge figures were then used to correct the plate scale figures. The moisture content (MC, wet basis) was determined in total on 9 wood chips samples (each sample=1 L). Samples were collected and weighed fresh in the field and then dried in a ventilated oven at 70°C until a constant weight was reached. The fuel consumption of each machine was measured by starting with a full tank and refilling it at the end of the working day.

2.6 Machines cost

Machine costs were calculated using the method described by Eliasson (2013) (Table 2). Machine service life estimates as well as the costs of insurance, repairs and services were obtained directly from the machine owners. The labour cost was set to 20 € per PMH_{15}, inclusive of indirect salary costs. The calculated operational cost of all machines was increased by 20% to account for overhead costs (cf. Hartsough 2003).

2.7 Soil compaction and tree damage measurements

In the San Daniele study site, stand damage and soil compaction measurements were carried out. Stand damage was determined by inspecting all standing trees left in each plot after harvest. Wounds with an exposed area smaller than 10 cm^2 were not recorded, as they had little impact on a tree's health or wood quality (cf. Whitney 1991).

Soil compaction was determined by sampling 10 cores per plot: 5 on inter-rows driven over by the machines and 5 on inter-rows that had not been driven over by machinery representing undisturbed soil conditions. Cores were collected in rings made of thin walled stainless steel tubing, with an internal diameter of 8 cm and a height of 5 cm, corresponding to a volume of 250 cm^3. Rings were pushed into the soil, down to a depth of 5 cm, after removing the litter layer. These rings were then removed from the soil and the samples were trimmed and placed into sealed plastic bags (one sample per bag). Samples were weighed before and after being oven-dried until they reached a constant weight at 70°**C**. These data were used to calculate the bulk density and the moisture content of each sample.

Once in the laboratory, the soil was passed through a 2 mm sieve in order to calculate total porosity. The ground pressure applied by the loaded axles of both harwarders was calculated as described by Komandi (1990), by using the maximum axle loads obtained from the portable scales as input data.

2.8 Analysis and statistics

Analysis of variance (ANOVA) was used in order to analyse initial stand and removal properties. A general linear model (GLM) was used for analysis of time consumptions, productivities and costs. Differences between the methods were examined using Tukey's post-hoc HSD pair-wise tests of means.

The properties of the initial stand, the removal characteristics, time consumption, productivities, costs, damage and soil impact in each plot were compared using the model:

$$\gamma_{ij} = \mu + \alpha_i + \beta_j + \alpha_i \quad \beta_j + \varepsilon_{ij} \qquad (1)$$

Where:

- μ overall mean,
- α harwarder: »small« (SH) vs. »large« (LH),
- β product: »whole trees (WT)« vs. »integrated (IH)«,
- ε random error.

Removal per ha and tree mass were tested as covariates in the GLM.

Harvesting costs for the different harwarders and treatments were then modelled as a function of harvested tree mass and annual usage of the equipment. Statistics were carried out using Minitab® (Minitab Inc.).

3. Results

3.1 Properties of removal

In total, 140 fresh t (88 odt) were harvested during the experiment. The MC of the biomass ranged from 34% to 42%, with a mean value of 38%. The thinning intensity reached almost 50% of trees/ha, which corresponded to an average removal of 45 fresh t/ha (28 odt/ha) (Table 3). The mean tree mass harvested varied between 57 and 114 fresh kg (from 35 to 71 odkg) (Table 3). The average DBH (weighted by basal area) before thinning was 13 cm, the average DBH of the remaining trees was 14 cm after the thinning operation. The percentage of removed trees and the removal mass per ha were similar for the four different treatments, while the average harvested tree size was slightly larger in treatments with the small harwarder, with this difference being close to significant (Table 3). The large harwarder extracted 9% more firewood biomass compared to the small machine (Table 3) and this difference was significant. The forwarding distance was, on average, 217 m for all treatments (Table 3).

Table 3 Properties of removals

Harwarder		SH		LH		ANOVA *p*-value*	
Product		WT	IH	WT	IH	Harwarder *p*-value	Product *p*-value
Harvested plots, n		4	4	4	4		
Removal intensity, % number of trees	Mean	49	48	49	49	0.815	0.771
	Sd.	3	3	6	6	–	–
	Min.	44	45	41	40	–	–
	Max.	51	51	54	56	–	–
Removal fresh mass, tha^{-1}	Mean	49	50	39	42	0.262	0.790
	Sd.	19	11	10	19	–	–
	Min.	24	40	27	19	–	–
	Max.	65	65	47	66	–	–
Removal fresh mass per tree, kg	Mean	88	96	71	75	0.055	0.0531
	Sd.	22	21	8	17	–	–
	Min.	63	68	60	57	–	–
	Max.	108	115	77	98	–	–
Extraction distance, m	Mean	231	210	218	211	0.860	0.860
	Sd.	101	77	95	68	–	–
	Min.	140	125	100	150	–	–
	Max.	360	311	332	282	–	–
Firewood, % total fresh mass	Mean	–	36	–	45	**<0.001**	–
	Sd.	–	1	–	2	–	–
	Min.	–	35	–	43	–	–
	Max.	–	37	–	47	–	–

Note: Fresh mass, for wood with a moisture content of 38%. *The bold *p*-values indicate statisticalyl significant difference ($p \leq 0.05$). The *p*-value for interactions harwarder × product are >0.8 in all cases (not shown in this table)

3.2 Work efficiency

The total study time for the two harwarders (including machine delays) was 45.9 hours, of which delay time represented 3.7 hours (8.1%). The incidences of delays on the PM_0 time for the SH and LH was 10.1% and 7.3%, respectively.

A full load for the SH contained, on average, 3.2 t (2.0 odt) (Sd=0.7 t) of whole-tree biomass, 2.7 t (1.7 odt) (Sd=0.5 t) of firewood logs and 1.7 t (1.1 odt) (Sd=0.3 t) of tree tops, corresponding respectively to 70%, 54% and 34% of the load capacity (5 t) for this machine. A full load of the LH contained 4.2 t (2.6 odt) (Sd=1.0 t) of whole-tree biomass, 4.2 t (2.6 odt) (Sd=1.2 t) of firewood and 3.7 t (2.3 odt) (Sd=1.0 t) of tree tops corresponding respectively to 42%, 42% and 37% of the load capacity (10 t). The average driving speed was 1.1 m/s (Sd=0.2 m/s) and 1.5 m/s (Sd=0.4 m/s), respectively, for the SH and LH.

Of the total recorded PM_0 time, the felling and loading work represented 78%, extraction work 12% and unloading work 10%. The tree mass had a significant effect on the total PMH_0/t, due to the fact that felling/loading efficiency was significantly dependent on tree size (Table 4). However, the tree size had no significant effect on driving time and it was not significant for unloading work. The removal (t/ha) was

Table 4 Analysis of variance table for the GLM harvesting time consumption, productivity and cost

	Variables	*DF*	Adj SS	Adj MS	*F*	*p*-value*
Felling and loading, PMH_0/t	Tree mass, kg	1	0.73565	0.73565	27.88	**0.000**
	Harwarder	1	0.32407	0.32407	12.28	**0.006**
	Harwarder × Tree mass, kg	1	0.14028	0.14028	5.32	**0.044**
	Product	1	0.47226	0.47226	17.90	**0.002**
	Harwarder × Product	1	0.01313	0.01313	0.50	0.497
	Residual error	10	0.26386	0.02639	–	–
Driving, PMH_0/t	Tree mass, kg	1	0.009277	0.009277	4.01	0.073
	Harwarder	1	0.024931	0.024931	10.79	**0.008**
	Harwarder × Tree mass, kg	1	0.006282	0.006282	2.72	0.130
	Product	1	0.040255	0.040255	17.42	**0.002**
	Harwarder × Product	1	0.025437	0.025437	11.01	**0.008**
	Residual error	10	0.023109	0.002311	–	–
Unloading, PMH_0/t	Tree mass, kg	1	0.000130	0.000130	0.09	0.768
	Harwarder	1	0.008940	0.008940	6.34	**0.031**
	Harwarder × Tree mass, kg	1	0.000310	0.000310	0.22	0.649
	Product	1	0.000479	0.000479	0.34	0.573
	Harwarder × Product	1	0.001261	0.001261	0.89	0.367
	Residual error	10	0.014109	0.001411	–	–
Total net time, PMH_0/t	Tree mass, kg	1	0.88851	0.88851	23.97	**0.001**
	Harwarder	1	0.10038	0.10038	2.71	0.131
	Harwarder × Tree mass, kg	1	0.07710	0.07710	2.08	0.180
	Product	1	0.74988	0.74988	20.23	**0.001**
	Harwarder × Product	1	0.00009	0.00009	0.00	0.962
	Residual error	10	0.37063	0.03706	–	–
Gross productivity, t/PMH_{15}	Tree mass, kg	1	1.138	1.138	22.25	**0.001**
	Harwarder	1	0.031	0.031	0.61	0.453
	Harwarder × Tree mass, kg	1	0.014	0.014	0.27	0.612
	Product	1	1.097	1.097	21.45	**0.001**
	Harwarder × Product	1	0.050	0.050	0.98	0.346
	Residual error	10	0.512	0.051	–	–
Harvesting cost, €/t	Tree mass, kg	1	102.32	102.32	18.10	**0.002**
	Harwarder	1	72.47	72.47	12.82	**0.005**
	Harwarder × Tree mass, kg	1	18.31	18.31	3.24	0.102
	Product	1	88.99	88.99	15.74	**0.003**
	Harwarder × Product	1	3.39	3.39	0.60	0.456
	Residual error	10	56.53	5.65	–	–

Note: Fresh mass, for wood with a moisture content of 38%. *The bold *p*-values indicate statistically significant difference ($p \leq 0.05$)

strongly correlated (p<0.001) to the harvested tree mass, which explained 60 % of its variability. For this reason, only the tree mass was used as a covariate in the analyses. The interaction of tree mass and harwarder type was significant for the felling and loading work-time; the SH was more sensitive to an increase in tree size than the LH. The type of harwarder had a significant effect on all time elements: the SH was more efficient for the felling and loading work, while the LH was more efficient for the driving and unloading work. The difference in total PM_0 time consumption per t was below 5% in the average studied conditions and it was not significant (Tables 4 and 5).

The type of product had a significant effect on the PM_0 time consumption: the WT treatment had, on average, a 16% lower time consumption per t than the IH treatment and this reduction was significant in the case of the SH (Tables 4 and 5).

Table 5 Corrected averages according to the GLM for the average tree mass studied (82 kg), minimum and maximum time consumptions, productivities and costs

Harwarder	SH		LH	
Product	WT	IH	WT	IH
Harvested plots, n	4	4	4	4
Felling and loading, PMH_0/t	0.167[a]	0.200[ab]	0.225[b]	0.271[c]
Min.	0.139	0.158	0.231	0.217
Max.	0.183	0.220	0.279	0.323
Driving, PMH_0/t	0.036[b]	0.057[a]	0.019[c]	0.022[c]
Min.	0.026	0.044	0.013	0.019
Max.	0.041	0.070	0.028	0.024
Unloading, PMH_0/t	0.042[a]	0.039[a]	0.015[b]	0.016[b]
Min.	0.035	0.035	0.011	0.013
Max.	0.047	0.041	0.018	0.017
Total net time, PMH_0/t	0.245[a]	0.295[b]	0.259[ab]	0.308[b]
Min.	0.208	0.244	0.256	0.252
Max.	0.271	0.325	0.318	0.360
Gross productivity, t/PMH_{15}	3.46[a]	2.81[b]	3.19[ab]	2.77[b]
Min.	3.08	2.57	2.63	2.32
Max.	4.02	3.43	3.26	3.32
Harvesting cost, €/t	18.27[a]	22.50[a]	29.71[b]	34.22[c]
Min.	15.75	18.46	29.03	28.56
Max.	20.52	24.58	36.09	40.89

Note: weights are fresh, for wood with a moisture content of 38% Different superscript letters in individual rows indicate a significant difference ($p \leq 0.05$) between treatments according to Tukey's HSD tests of means

3.3 Productivity and cost

On average for all treatments, the gross harvesting productivity (including felling, extraction and delay time) varied from 2.3 to 4.0 t/PMH_{15} (1.4–2.5 odt/PMH_{15}). The average fuel consumption was 4.5 and 8.0 l/PMH_{15} for the SH and LH, respectively.

The harvesting cost per t was 34–39% significantly lower for the SH (Table 5). The IH treatment cost from 4.2 to 4.5 €/t more than WT, and the combination of IH treatment and the large harwarder cost significantly more (Table 5).

Two cost models (Eqs. 2 and 3) for the SH (C_{SH}) and LH (C_{LH}) harwarder, based on the results in Table 4 (all significant variables included) were obtained:

$$C_{SH} = 29.170 - 0.105 \times Tm - 1.932 \times P \text{ [€/t]} \quad (2)$$

$$R^2 \text{ adj.} = 0.90,\ F = 34.3,\ p = 0.001$$

$$C_{LH} = 53.152 - 0.252 \times Tm - 2.402 \times P \text{ [€/t]} \quad (3)$$

$$R^2 \text{ adj.} = 0.93,\ F = 50.1,\ p = 0.001$$

Where:

Tm tree mass, kg,

P product type, dummy variable (0=IH, 1=WT).

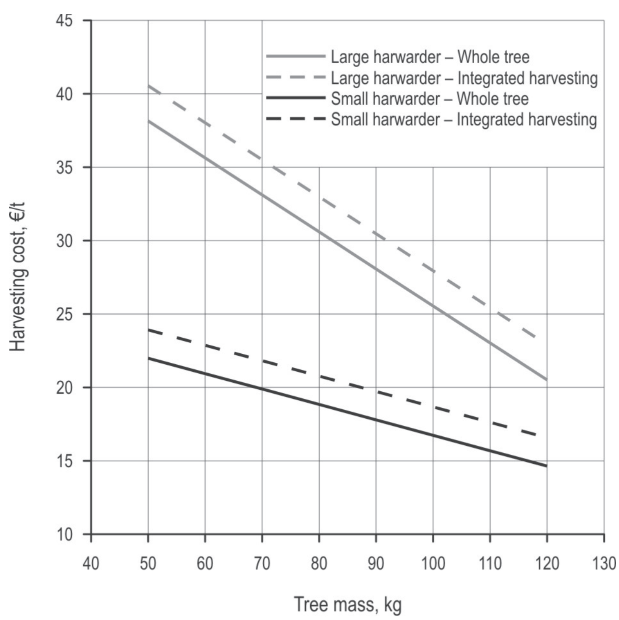

Fig. 1 Harvesting cost as function of tree mass for the four different treatments (calculated using Eqs. 2 – 3 with the average removal fresh mass set to 45 t/ha)

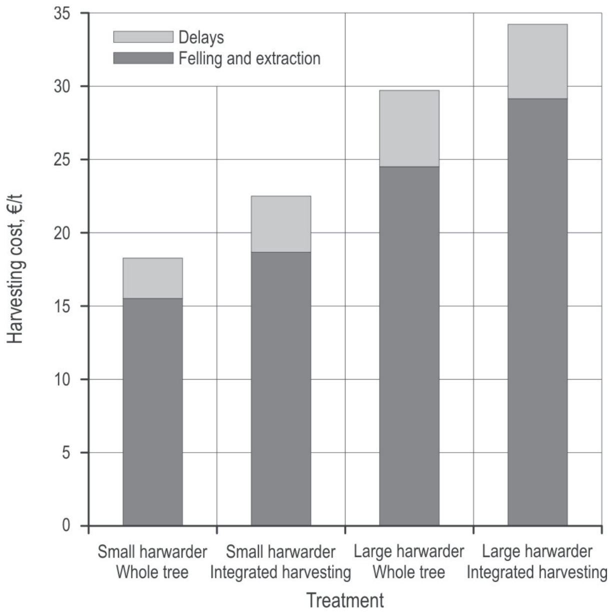

Fig. 2 Average harvesting cost by treatment and activity in the field study. (Calculated with the average removal fresh mass set to 45 t/ha and average removal tree fresh mass set to 82 kg)

If the tree size is increased from 50 kg to 120 kg, the harvesting cost for the SH and LH is reduced by 32% and 45%, respectively (Fig. 1).

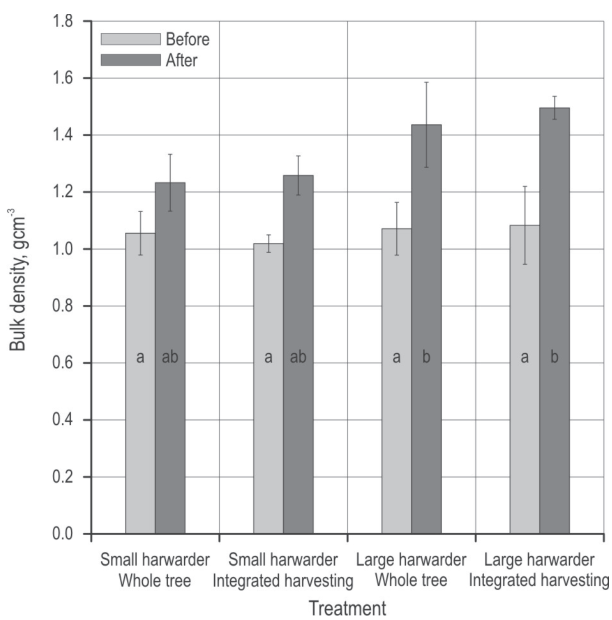

Fig. 3 Average soil bulk density before and after machine activity for the four analysed treatments (n=3 per column, the error bars represent the standard deviations). Columns that do not share any letter are significantly different ($p \leq 0.05$) according to Tukey's HSD tests of means

The harvesting cost at the average stem mass (82 kg) varied between 18 and 34 €/t (30 and 55 €/odt). It was one third lower for the SH system (Table 5). Of the total harvesting cost, felling and extraction accounted for 82% to 85%, and delays accounted for 15% to 18% (Fig. 2).

3.4 Soil compaction and frequency of tree damage

The initial soil densities were similar for the different plots (Fig. 3).The average soil bulk density increased from 1.04 to 1.25 gcm^{-3} for the SH and from 1.08 to 1.47 gcm^{-3} for the LH (Fig. 3). The effect was significant for the LH (p=0.004) (c.f. Fig. 3). The soil porosity was, on average, 40 % and decreased to 30% for the SH and 20% for the LH. The effect was significant for the LH (p=0.01).

Damage to residual trees varied between 1% and 4% of the total number of remaining trees. Mean damage frequency was slightly higher for the LH and the WT treatment, but the differences were not significant.

4. Discussion

The SH was found to be more time-efficient for the felling and loading work compared to the LH. This can be explained by the fact that the SH direct-loaded the cut trees while the LH was unable to direct-load. The inter-row space in the test plantations was too narrow for direct-loading of the LH. Many studies indicate that direct-loading is more efficient than separate loading (Andersson and Eliasson 2003, Talbot et al. 2003, Ringdahl et al. 2012, Wester and Eliasson 2003).

The LH felling and loading work efficiency per t increased rapidly with harvested tree size, while the SH efficiency was less sensitive to different tree sizes. This could suggest that the SH was already operating close to the limit of its size capacity and, therefore, increases in tree size were balanced by proportional increases in working time. The LH was more efficient for the transportation work due to both higher driving speed and larger load capacity. In addition, the LH had higher efficiency for the unloading work since it was equipped with a timber-grapple, which had a larger handling capacity than the grapple-saw used on the SH.

A different share of harvested firewood was obtained for the two machines, which could be due to the different ways trees were handled by the operators. The main instruction given to them was to produce firewood logs up to the lowest large branch. In each case, the operators selected the bucking point. The integrated harvesting of firewood logs and tree tops reduced the felling/loading and extraction work efficiency, compared to whole-tree sections. This is explained as follows:

⇒ in the IH treatment, the wood needed to be sorted into separate loads into the stand, while in the WT no sorting took place,

⇒ in the IH treatment, a firewood load contained a similar mass to a whole-tree section load, but a full load of tree crowns contained 12–47% less mass than loads of whole-tree sections.

The productivities of the two harwarders were similar. The productivity levels for the LH are very close to those reported in the literature for similar machines in early thinning operations in boreal forests in Scandinavia (c.f. Laitila and Asikainen 2006, Di Fulvio and Bergström 2013). The productivity of the small Vimek harwarder used in this study was almost twice as high compared to a previous model of the machine studied when used in the early thinning of *Pinus contorta* (Nordin 2011). However, in Nordin´s (2011) study, the ground conditions were much more challenging than in this study. This may help explain the large difference in productivities especially when coupled with the fact that the engine power has increased 2.4 times and the machine load capacity has increased by 35% on this new model, resulting in a 29% larger load for this study.

The main asset of an LH is the flexibility of the machine. For example, it can be used for a variety of operations, i.e. from early thinning to final felling work of trees with stem volumes up to 0.3 m^3. The SH used in this study is designed for early thinning and the purchase of an SH depends on the ability to secure enough thinning work on a yearly basis. The LH may, however, complement the thinning of a small number of plantations with other, more conventional, forest operations. Furthermore, the harvester head on the LH is better suited for processing logs than the simple grapple-saw on the SH, which provides a higher potential for value recovery, as saw, pulp and firewood logs can attract a higher price than energy chips (Spinelli et al. 2013). Thus, it seems that the LH is likely to have a higher annual utilization than the SH. A sensitivity analysis was carried out under the assumption that both machines were exclusively used for the early thinning of plantations on farmland. The annual harvested mass varied from 1,000 to 6,500 fresh t. The annual utilization (PMH_{15}/year) of each harwarder was then re-calculated, by assuming the mean harwarder productivity (t/PMH_{15}) as in Table 5.

The analysis showed that the harvesting cost is below 35 €/t for the LH, if the machine harvested at least

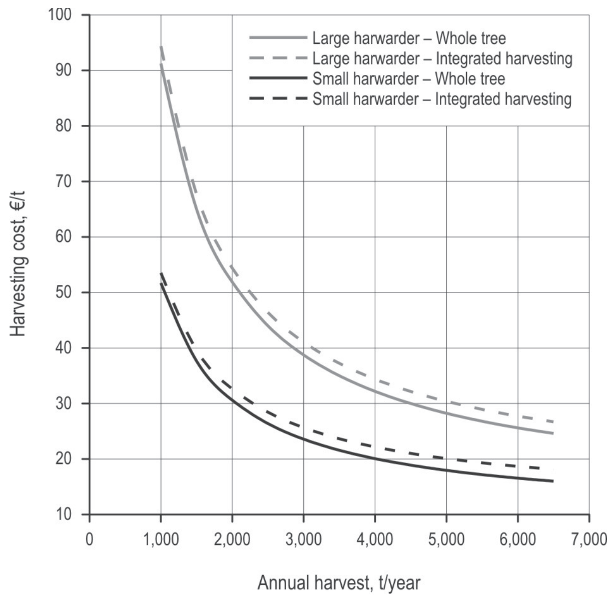

Fig. 4 Harvesting cost as a function of annual harvested biomass. (Calculated with the average removal fresh mass set to 45 t/ha and average removal tree fresh mass set to 82 kg)

4,000 t per year (i.e. at least 1,200 PMH_{15}/year) (Fig. 4 and 5); this figure corresponds to about 90 ha per year given the average removal of 45 t/ha. Assuming a maximum utilization of 2,000 PMH_{15} per year, one single machine could not harvest more than 150 ha per year.

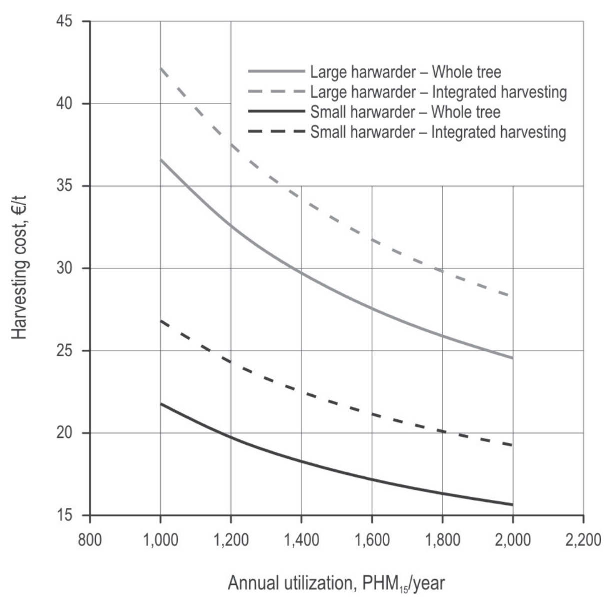

Fig. 5 Harvesting cost as a function of annual usage of harwarders for four treatments. (Calculated with the average removal fresh mass set to 45 t/ha and average removal tree fresh mass set to 82 kg)

The two harwarders cost the same per t for WT when the LH harvests 6,500 t/year and the SH harvests 3,000 t/year (Fig. 4). These figures correspond to an annual utilization of 900 and 2,000 PMH_{15}/year, respectively, for the SH and LH (Fig. 5). For the IH harvesting, they cost the same per tonne if the SH is used for 1,000 PMH_{15}/year and the LH for 2,000 PMH_{15}/year (Fig. 5).

At any annual utilization rate, both harvesting chains presented in this study resulted in a lower harvesting cost than any of the motor-manual alternatives studied in similar conditions by Magagnotti et al. (2011, 2012). If the current labour cost and fuel prices are taken into account, the motor-manual thinning costs between 25 and 40 €/t, while the mechanized chains tested at the time cost between 20 and 22 **€/t. T**he actual mechanized harvesting system studied cost between 18 and 34 €/t. Therefore, the SH might offer cost savings compared to the other mechanized options tested before. In contrast, the LH offers no cost benefits over conventional dual-machine systems.

The harwarder options offer additional savings on relocation cost, especially considering that both harwarders tested are road-legal, which means that they can relocate independently over short distances. This may offer some benefits over the other mechanized chains such as e.g. excavator based feller bunchers that need dedicated transportation for relocation (Väätäinen et al. 2006b). This advantage of the harwarder becomes especially important with farmland forests in Italy, which are typically fragmented and may have an average area below 1 ha (Alberti et al. 2005).

The impact on both stands and soil was minor in this study and was near to the levels recorded for motor-manual operations, where the frequency of residual stand damage was 3.4% and the increase in soil bulk density 17% (Magagnotti et al. 2011). In particular, soil bulk density after machine activity in this study was still below the 1.7–1.8 gcm^{-3} range considered as the threshold value for optimal root elongation (Heilman 1981). The significant soil compaction in the case of the LH could be related to the higher ground pressure produced, which was calculated to 270 kPa, compared to a ground pressure of 220 kPa obtained for the SH using Komandi's (1990) formula. The compaction found can also be related to the high moisture content recorded at the time of harvest (21%), which was similar on all harvested plots. The depth at which the observations for evaluation of compaction and porosity were made seemed to be appropriate, as the main impacts of wood extraction are generally concentrated within the first 10 cm layer (Ampoorter et al. 2010), especially in Mediterranean and sub-Mediterranean soils (Makineci et al. 2007).

4.1 Strengths and weaknesses of the study

The two harwarder systems were studied under similar thinning conditions with no significant differences in thinning intensity and biomass removal per ha. Somewhat larger trees were, however, harvested with the SH, and this could have had some effect on our results; however this effect would be small as the tree size was used as a covariate when analysing time consumption and costs. Removal intensity, biomass yield and tree mass are similar to the ones reported by previous studies of the same type of operations in similar plantations (Magagnotti et al. 2011, Magagnotti et al. 2012), suggesting that the test sites are representative of average work conditions.

A plot length of 50 m was too short for accumulating a full load when the stand stocking was low. For this reason, the extraction times were corrected for partial loads, occasionally derived from study design. In such a case, machine travel time was corrected using the ratio between the actual scaled load and the reference full load. The latter was assumed to be the maximum load actually carried during the whole study for each machine and assortment, which was visually assessed as the »optimum« load size, when the bunk was clearly unable to accommodate any more wood.

In order to remove the effect of different forwarding distances, the extraction time for each plot was corrected in each single plot by using the speed of the machine in the plot and the average forwarding distance recorded over the whole study.

Both operators were professionals and had worked with their respective machines for several years in thinning operations. However, productivity levels between harvester operators have been noted to vary significantly by up to 40% in thinning (Ovaskainen et al. 2004).

The LH needed to change its configuration from a harvester to a forwarder and this extra time was not accounted for in this study (ca. 20 minutes for each configuration change c.f. Di Fulvio and Bergström 2013). This time can be significant in small stands and it will be less relevant as the stand area or removal volumes per site increase.

4.2 Future work

The results of this and other studies (Magagnotti et al. 2011, Magagnotti et al. 2012) provide information on harvesting systems for selective thinning of hardwood plantations on farmlands. More detailed analyses of the whole supply system from the plantation to the end users are needed, where the processing and transportation of firewood and whole tree sections to their respective customers are also included. These kinds of analyses can be carried out using simulations of machines working in different plantation environments (i.e. in terms of tree sizes, growing stocks and plantation sizes) with the introduction of factors such as market demands and biomass prices as stochastic variables.

5. Conclusions

The main objective of this work was to study the productivity and cost efficiency of harwarder systems in fuel wood thinning of hardwood plantations considering: two machine sizes (small and large) and two products harvested (1: tree-parts of whole trees and 2: firewood logs and tree tops).

The productivity of the harvesting work was, on average, 14–24% higher for removal of whole-tree parts in comparison to the extraction of firewood logs and tree tops. This difference was significant for the SH and close to significant for the large harwarder.

The SH was more efficient for felling and loading, while the LH was more efficient in the extraction work. Therefore, the productivity was similar for the two harwarders in the studied conditions.

The harvesting cost was, on average, 18.3–29.7 €/t when harvesting whole-tree parts and was 22.5–34.2 €/t for the harvesting of firewood and tree tops. The SH cost significantly less for both treatments (WT and IH).

The system with the SH was more cost-effective due to the lower hourly operational cost of the harwarder, which was mainly as a result of the lower machine investment cost. For an annual utilization time of 2,000 hours for the LH, the SH must be used for at least 900 hours/year when harvesting whole-tree parts to equal the cost-efficiency of the LH and 1,000 hours/year for an integrated harvest.

The main drawback of the SH is the fact that it is limited to thinning works. Therefore it requires securing of enough thinning work during the year to reach sufficient utilization and a reasonable hourly cost compared to a larger machine. This study indicates that thinning of farmland plantations may offer good working conditions (e.g. flat areas, absence of roughness, schematic work pattern) for a small harwarder, but they remain challenging for a large machine due to the relatively small trees handled and the limited manoeuvrability in the stands. The LH is, thus, more efficient in stands with long forwarding distances (e.g. large plantation areas) and in the removal of large tree sizes.

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